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ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT: ADOT-RS-14 (158) FINAL REPORT — PORTLAND CEMENT CONCRETE

UTILIZATION OF WASTE BOILER ASH IN HIGHWAY CONSTRUCTION IN ARIZONA

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December 1976

Prepared for:
Arizona Department of Transportation
206 South 17th Avenue
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in cooperation with
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16. Abstract

Waste boiler ash (fly ash)is produced by several coal-fired power generating plants in and adjacent to Arizona. A literature search, laboratory test program and analysis of test data indicate that available fly ashes can be advantageously used as admixtures in portland cement concrete for highway construction. Compressive strength, flexural strength, resistance to sulfate attack and freeze-thaw durability are included in the laboratory test series. Test data are utilized in the development of a mix design procedure aimed at optimizing the proportions of fly ash and portland cement.

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FINAL REPORT

UTILIZATION OF WASTE BOILER ASH IN HIGHWAY CONSTRUCTION IN ARIZONA

PART I - PORTLAND CEMENT CONCRETE

by

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and

M. Kent Hamm, P.E.

Submitted to

Arizona Department of Transportation

Highways Division

for

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Sponsored by

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Federal Highway Administration

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IMPLEMENTATION STATEMENT

The search for more efficient construction material and the problem of industrial waste disposal have been combined in the development of uses for waste boiler ash (fly ash) produced by coal-fired power generating stations. Fly Ash is a pozzolan, a material with cementitious properties which can be utilized in many construction material applications. This report evaluates the use of fly ash that is available from four sources. Part I evaluates the use of fly ash in portland cement concrete. Part II evaluates the use of fly ash combined with lime in soil stabilization. Chapter 8, Part I presents a mix design procedure and Chapter 6, Part II presents Iso-Strength curves in mix design procedures. A first estimate of the mix proportions may be developed from the most appropriate family of Iso-Strength curves. Target strength should be retained after allowing for loss due to saturation. Cost data can be used to establish the proportions of lime and fly ash in an economical range. Mix design procedures as outlined in the report will be incorporated into ADOT pavement design and evaluated.

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ABSTRACT

Waste boiler ash (fly ash) is produced by several coal-fired power generating plants in and adjacent to Arizona. A literature search, laboratory test program and analysis of test data indicate that available fly ashes can be advantageously used as admixtures in portland cement concrete for highway construction. Compressive strength, flexural strength, resistance to sulfate attack and freeze-thaw durability are included in the laboratory test series. Test data are utilized in the development of a mix design procedure aimed at optimizing the proportions of fly ash and portland cement.

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHO	American Association of State Highway Officials
ACI	American Concrete Institute
ADOT	Arizona Department of Transportation
ASTM	American Society for Testing and Materials
A, B	Constants
Btu	British thermal unit
^{o}C	Degrees Celsius
cc	Cubic centimeters
CD	Coefficient of determination
CLC	Coefficient of linear correlation
cm	Centimeters
CM	Cementitious material
cy	Cubic yard
e	Natural logarithm base (2.718---)
ETL	Engineers Testing Laboratories, Inc.
^{o}F	Degrees Farenheit
F	Fly ash to portland cement weight ratio
FA	Fly ash
ft, ft^3	Feet, cubic feet
gal.	Gallons U.S.
gm	Grams
in.	Inch
Kg	Kilogram
K	Constant
KW	Kilowatt
k	Fly ash efficiency factor
KWH	Kilowatt-hour
lb.	Pound
MW	Megawatt
m, m^3	Meter, cubic meter
n	Number of samples
psig	Pounds per square inch gauge
PCA	Portland Cement Association

LIST OF ABBREVIATIONS AND SYMBOLS (continued)

PC	Portland cement
PC'	Portland cement equivalent
R	Flexural strength
s	Standard deviation
sk.	Sack (94 pounds portland cement)
σ	Compressive strength
σ_{cyl}	Compressive strength, molded cylinder
σ_{core}	Compressive strength, drilled core
σ_{28}	Compressive strength at subscript age
V_1	Within-test coefficient of variation
Vol.	Volume
W	Water (usually weight)
X	Independent variable
Y	Dependent variable

CONVERSION FACTORS

To convert from	To	Multiply by
Cubic foot	Cubic meter	2.832×10^{-2}
Cubic inches	Cubic meter	1.639×10^{-5}
Cubic yards	Cubic meter	7.646×10^{-1}
Foot	Meter	3.048×10^{-1}
Gallon (U.S. liquid)	Cubic meter	3.785×10^{-3}
Inch	Meter	2.540×10^{-2}
Pound-force	Kilogram-force	4.536×10^{-1}
Pounds per square inch	Kilograms per square centimeter	7.031×10^{-2}
Sack (U.S. cement)	Kilograms	4.264×10
Tons	Kilograms	9.072×10^{2}
Degrees Farenheit	Degrees Celsius	*

* $^{o}C = (5/9)\ (^{o}F-32)$

PROJECT SUMMARY

Coal-fired steam generating stations in and around Arizona produce millions of tons of waste boiler ash (fly ash) per year, most of which is not utilized in any way. Research has shown fly ash to possess pozzolanic properties thereby making it potentially useful, as a cementitious material, in a variety of construction applications.

The Arizona Department of Transportation, in October, 1974, commissioned Engineers Testing Laboratories, Inc. to undertake a study for the purpose of evaluating potential uses of fly ash in Arizona highway construction. The program was to serve the multiple objectives of developing a low cost construction material, utilizing a previously wasted by-product, and aiding in the conservation of the non-renewable resources, lime and portland cement.

The study was divided into two parts. Part I concerned the utilization of fly ash in portland cement concrete for Arizona highway construction. Included were a literature review, laboratory test program, engineering analysis of data, and the development of a mix design method. The laboratory procedures were directed toward evaluation of compressive strength, flexural strength, freeze-thaw durability and resistance to sulfate attack. Forty-eight mix designs were tested in the strength test series. A number of the mixes were then subjected to the durability and soundness test series. Strengths were determined to be predictable utilizing the proposed mix design method. Fly ashes from the four available sources were found to be beneficial admixtures for portland cement concrete.

An interim report was submitted to the Arizona Department of Transportation in January, 1976. The purpose of the

interim report was to present the preliminary fly ash concrete mix design procedure for review prior to the completion of the study.

Part II concerned the utilization of fly ash in soil stabilization for Arizona highway construction. The study program included a literature review, laboratory test series, engineering analysis of data and the development of a mix design procedure for lime-fly ash stabilized soil. Four typical Arizona soils were utilized in the test series, with fly ash from the four principal sources available in Arizona. Laboratory evaluations included combinations of zero to eight percent lime and zero to thirty percent fly ash for each soil type and fly ash source. Unconfined compressive strength, wet-dry durability and freeze-thaw durability were evaluated in the test series. The fly ashes were found beneficial in varying degrees, depending primarily on soil characteristics.

The two year project was completed with the general conclusion that available fly ash could be efficiently utilized in highway construction in Arizona.

CHAPTER 1. INTRODUCTION

The search for more efficient construction materials, and the problem of industrial waste disposal have been combined in the development of uses for waste boiler ash (fly ash) produced by coal-fired power generating stations. Fly ash is a pozzolan, a material with cementitious properties which can be utilized in many construction materials applications. The purpose of this report is to evaluate the use of fly ash in portland cement concrete.

The study has been conducted through literature search, laboratory testing and engineering analysis of the data developed. In carrying out the literature search, an effort was made to review all English language literature pertinent to the subject, with no regard for geographic origin. The laboratory studies utilized fly ash from the four principal sources which were found to be available to the Arizona construction market. Materials other than fly ash were each obtained from a single source thereby making fly ash quality the principal variable in the test program. Test series were designed to evaluate compressive strength, flexural strength, resistance to sulfate attack and resistance to deterioration from freezing and thawing.

Review of the literature and engineering analysis of the test data culminated in the development of a mix design procedure for normal weight portland cement concrete using fly ash as an admixture.

The results of the literature survey are presented in the chapter entitled Literature Review. Comment on the literature has been categorized by subject, for convenience (i.e., compressive strength, workability, durability).

References have also been organized by subject in the Subject Index to References immediately following the References near the end of the report.

Laboratory test procedures and results are presented in the middle chapters of the report along with analyses of of the data. The principal topics, strength and durability, are the subjects of separate chapters.

The mix design chapter includes an introductory evaluation of methods presently in use and a final section on evaluation of the proposed mix design method. The middle sections of the chapter can be independently used as a working outline for the proposed mix design method.

Information relative to the production and quality of fly ash from sources used in the study has been placed in an appendix since the evaluation of time variation in fly ash quality was not a principal objective of the program.

CHAPTER 2. LITERATURE REVIEW

2.1 Historical Development

2.1.1. Ancient Applications

In the third century B.C., the Roman builders made a significant discovery. Near Vesuvius were deposits of sandy volcanic ash, which when added to lime and water, made a cement which dried to rocklike hardness and even hardened under water. They called this material "pulvis puteolanus". By mixing this cement with sand and gravel they made concrete. First use of this material was as a filler between veneer finishes since durability to exposure was questioned. Nonetheless, some of the more daring builders of that time began using the material in exposed construction and surprisingly found the durability satisfactory. Thus, the material use spread widely. Structures, the Colosseum and the Basilica of Constantine, and distribution systems, the Clocaca Maxima and the Aquaducts, were just a few of the facilities built utilizing this new material. Many of these structures still exist today and attest to the durability of the new found material.

The Roman method of making cement, combining lime and pulverized volcanic ash, was essentially the only method employed until 1824, although numerous processes had been attempted. At that time, the first successful process of artifically combining and calcifying clay and limestone to form a hydraulic cement was realized. With the development of a manufacturing process to produce high quality hydraulic cement, known today as portland cement, the use of natural cementing agents declined rapidly.

The natural material employed by the Romans is classified today as a pozzolan. A pozzolan is defined as a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Pozzolans may be either natural materials or synthetic materials which consist of glassy materials produced by rapid cooling of molten silicate mixtures. Fly ash, the finely divided residue that results from the combustion of ground or powdered coal and is subsequently collected from the flue gases, is an example of a synthetic pozzolan. Fossil fuel power plants are the major producers of the material.

Although fly ash was recognized as a pozzolanic material, little use was made of the product until the need arose for massive concrete structures possessing low permeability. Experience with portland cement concrete revealed that during the hydration process significant quantities of heat were generated. Release of this heat, during the later cooling period, cause the concrete to crack unless precautions were taken. Thus, the need arose to minimize the temperature rise during hydration and subsequent volume change without loss in strength. Pozzolanic cements which produce lower ultimate heat than portland cement and which liberate the heat at slower rates appeared to be advantageous. Additionally, it was recognized that during the hydration of portland cement a significant quantity of free lime was formed. The free lime present in the hardened concrete was susceptible to leaching from the concrete of hydraulic structures resulting in a more porous concrete. The incorporation of a pozzolanic material, which would chemically combine with the free lime to form a non-leachable cement component, was employed. These circumstances initiated a renewed interest in pozzolanic materials.

2.1.2. Use of Pozzolans in the United States

With development of the manufacturing process for portland cement, the abundance of suitable materials for processing, and superior quality control, concrete construction in the United States was almost exclusively confined to portland cement.

Use of pozzolanic materials was not seriously considered until governmental emphasis was directed toward implementation of large reclamation and hydro-electric programs. Most of these programs required construction of massive concrete structures. In 1911, the Bureau of Reclamation initiated an investigation into the use of pozzolans in concrete (20)*, and in 1915 the Bureau of Reclamation specified a natural pozzolan for the Arrowrock Dam. The first use of fly ash as a pozzolan by the Bureau of Reclamation was in the repair of the spillway tunnel at Hoover Dam in 1942. Following this project the Bureau of Reclamation began collecting fly ash samples from various locations and initiated an extensive testing program. As a consequence, fly ash was specified for use in Hungry Horse Dam. Numerous projects have since been constructed under Bureau of Reclamation authorization which contain fly ash as a pozzolan.

Initial use of fly ash by the Corps of Engineers was in the construction of Sutton Dam, West Virginia, in 1958 (102). Subsequently, fly ash has been used extensively by the Corps of Engineers. Concurrently the

*Numbers in parenthesis in this section and throughout the report correspond to source title listed in the Reference section.

Tennessee Valley Authority began using fly ash in concrete structures.

In most of the early applications, the minimization of the heat of hydration was the primary concern rather than the strength characteristic of the resulting concrete. Experience indicated that 25-30% substitution of portland cement by fly ash could be utilized while achieving an adequate strength level; however, the desired strength would not develop within the normal reference period, 28 days. Since construction for these projects extended over a considerable period of time, early strength development was not a requisite. However, on projects where the construction period was short, the knowledge of fly ash concrete possessing low early strength most certainly curtailed its utilization.

The major impetus to the use of fly ash in portland cement concrete is attributed to the research work of R. E. Davis, et al (16) published in 1937 and in later reports (15, 17, 18). Some of the significant findings of these researchers relative to the use of fly ash in concrete were:

1. Improved workability
2. Less segregation and bleeding
3. Water demand about the same or lower
4. Increased ultimate strength
5. Reduced shrinkage
6. Increased resistance to sulfates
7. Reduced heat of hydration
8. Reduced permeability

Interest and research in fly ash usage in concrete waned during the World War II period but renewed interest and extensive research was initiated in the late forties. During the early fifties, correlation of research and experience data was undertaken by committies of various technical societies and agencies (2, 9, 10, 13, and 99). In 1954, the American Society for Testing and Materials issued the first specification for fly ash usage in concrete. This initial specification viewed fly ash as only an admixture in portland cement concrete and specifically stated, "The use of fly ash as a direct substitute for portland cement is not within the scope of these specifications". Three years later, the Corps of Engineers issued a specification for pozzolans and the methods of sampling and testing pozzolans. Subsequently, an engineering manual establishing criteria for use of pozzolans was issued. Modifications were incorporated into the original ASTM specifications periodically; however, it was not until 1960 that a standard was issued to cover fly ash both as a pozzolan in portland cement concrete and as an admixture. With the issuance of recognized specifications, utilization of fly ash in portland cement increased; however, today approximately 42 million tons (3.8×10^{10} Kg) of fly ash are produced annually, whereas only 10% of the ash is utilized with only a minor percentage finding its way into concrete.

2.1.3. Highway Construction

The use of fly ash in portland cement concrete by the various highway agencies has been rather limited. First reported use was in the construction of twelve 488 ft. (149 m) test sections in Kansas in 1949. Available aggregate for this construction had long been considered responsible for severe map-cracking and abnormal expansion in concrete pavements. In an effort to reduce these effects, fly ash from the Chicago area was used to replace 25% of the portland cement in the standard mix. The fly ash was found effective in reducing surface cracking and eliminating map-cracking (94). In 1949, Larson (40), working for the State Highway Commission of Wisconsin, reported the results on a study of the effects of substitution of fly ash for portions of the cement in air-entrained concrete. His study lead to the installation of a 3.3 mi. (5310 m) test section. Field examination of the test section by Abdun-Nur (1) after 9 years of service indicated the pavement to be in good condition with no evidence of failure due to the concrete. Knowledge of the experimental work being conducted in Kansas spread to Nebraska and two experimental test roads, each approximately 6 mi. (9660 m) in length, were constructed utilizing fly ash. Results indicated the use of fly ash in the concrete presented no special problems in construction and the fly ash concrete was durable, high in strength and did not expand because of cement-aggregate reaction (95).

The Alabama State Highway Department has been the leader among the states in using fly ash in concrete pavements and structures with their first installation being in 1955. Their experience with fly ash has been so successful that to date over 660 mi. (1.06×10^6 m) of pavement have been constructed (28, 29, 30). Alabama is one of the few states which currently have a standard set of specifications for fly ash concrete. Alabama's experience (30) indicates that without regard to the benefits derived from the addition of fly ash to concrete, when based on the cost of the concrete without fly ash, the average cost of the fly ash mixture is less. Nevertheless, to date only eleven states have used fly ash in portland cement concrete.

2.1.4. Structural Uses

A rather limited amount of published data exists, relative to the use of fly ash as a pozzolan in structural concrete. Public contention that fly ash concrete possesses low early strength, a detriment to early form removal and rapid construction, may have accounted for the slow acceptance of fly ash concrete for structural uses. The leaders in the structural use of fly ash concrete have been the power utilities, particularly in the Chicago area. With their successful experience, architectural firms soon began specifying fly ash concrete for structures.

The Prudential Building in Chicago, a 41 story structure, contains a total of 100,000 cy (76,460 m^3) of fly ash concrete in the structural elements, ranging from the caissons to the light-weight concrete floors (33). It has been concluded that the use of fly ash was the prime factor for the remarkable absence of drying shrinkage cracks in the floors. Numerous other high-rise structures, John Hancock Center, Imperial Towers, Lake Shore Drive Apartments, Lake Point Tower and others, have incorporated fly ash in their construction. For the 5000 psi (350 Kg/cm^2) concrete specified for the Imperial Towers, only two cylinders fell below specifications, and the coefficient of variation was 2.88%. In the 20 story Lake Point Tower fly ash concrete designed for 7500 psi (530 Kg/cm^2) was used in all columns and shearwalls to the 17th floor. Twenty-eight day compressive strength test results indicated strength of 8100 psi (570 Kg/cm^2). Additional structures have been built incorporating fly ash concrete with the strength of 9000 psi (630 Kg/cm^2) and currently consideration is being directed to developing fly ash concrete possessing compressive strength as high as 11,000 psi (770 Kg/cm^2).

2.1.5 Specifications

As will be discussed later, fly ash varies from one power plant to another and from time to time in a given plant. Due to this variability, specifications have been established to use as a guide for assessing the general characteristics of the fly ash. The first specifications issued in 1954 by the American Society for Testing and Materials applied only to the use of fly ash as an admixture to concrete. Numerous modifications were later adopted and in 1960 specifications were issued relative to the acceptance of fly ash as a pozzolan. The current ASTM specification, Designation: C618-73, segregated all pozzolans into three classes; raw or calcined natural pozzolans, Class N; fly ash, Class F; and others, Class S. This specification is applicable for both the chemical and physical requirements of the pozzolanic material. The current ASTM specification forms the basis for all standard and/or special provision specifications issued by the state highway agencies. Table 2-1 contains the current ASTM specification for fly ash and the specifications issued by some of the state highway agencies and other public agencies. For the state specifications, entries have been designated only for those requirements which are in variance with the ASTM specification. In general, the state's specifications are more restrictive than the ASTM, particularly in regard to the loss on ignition requirement. Further, most of the states specify a maximum amount of fly ash which may be used in the concrete.

It is noted that a modification of ASTM Designation: C618-73 is presently under review by ASTM Committee C-9 and is to be voted upon for possible adoption. The review specification contains two classes for fly ash

TABLE 2-1. Specifications for Fly Ash

Property	ASTM C-618 Class F (6)	Std. Ala.	(1) S.P. Fla.	S.P. Ga.	S.P. Ind.	S.P. Ky.	S.P. Neb.	S.P. W.Va.	S.P. Mich.	S.P. Wisc.	Std. Minn.	(3) N. Dak. F1	(3) N. Dak. F2	Corps of Engrs.	Federal
pH min.		7.0		7.0											
SiO_2 %				40.0											
Al_2O_3 %		15.0		15.0											
Fe_2O_3 %															
Sum of Oxides % min.	70.0										45.0	70.0	5.0	70.0	75.0
MgO % max.		5.0		3.0								5.0		5.0	5.0
SO_3 % max.	5.0	3.0		3.0							12.0		7.0	4.0	4.0
Moisture % max.	3.0	1.0												3.0	3.0
LOI % max.	12.0	6.0	6.0	6.0	8.0	6.0	6.0	6.0	4.0	5.0	5.0		6.0	6.0	6.0
Available Alk. as Na_2O % max.	1.5 (2)	1.5									3.0		2.5	1.5	2.0
CaO % max.											35.0		35.0		
Free Carbon % max.							3.0								
Fineness cm^2/cm^3 min.	6500			3000 (4)										6500	6500
Retained #325 % max.	34	25		20.0					10.0		30.0	20.0	30.0	(7) N.S.	N.S.
Multiple Factor	255.0											150	150	N.S.	N.S.
Pozz. Act. Index - 28 Days % min.	85										75		75	75	75
w/lime psi min.	800													900	900
Water Requirement % max.	105													(5)	(5)
Shrinkage % max.	0.03	0.09												N.S.	N.S.
Soundness % max.	0.50													.50	.50
Expansion 14 day % max.	0.02													N.S.	N.S.
FA Proportion Specified			20% by wt.	25% by wt.	100 lb. per cy no red. in PC	94 lb. per cy		equal vol. to 1 bag	used 72 lb. FA to repl. 47 lb. PC	used 75 lb. FA per cy	10% by wt.	(8) 15%	(8) 15%		

NOTES:

(1) Special Provision
(2) Optional test
(3) Sub-bituminous and lignite coal sources
(4) cm^2/gm
(5) This specification requires that a mortar of fly ash pozzolan and 103 percent of the water content of the control shall have a flow equal to or greater than that of the reference mortar.
(6) Uniformity requirements not presented
(7) Not specified
(8) Weight or volume replacement not specified

pozzolanic material: Class F, fly ash derived from anthracite or bituminous coal; and Class C, fly ash derived from lignite or subbituminous coal. The review specification for Class F fly ash is the same as the current specification given in Table 2-1 with the following exceptions:

a) Blaine fineness requirement has been eliminated;
b) Pozzolanic Activity Index with portland cement has been lowered to 75% minimum;
c) Autoclave soundness has been increased to 0.8% maximum; and
d) a uniformity requirement on the fineness, as measured by the percent retained on the #325 sieve, has been added.

As this review specification has not been approved, the above are presented only for informational purposes and distribution of the Class C requirements is considered inappropriate at this time.

Other Federal agencies, Federal Housing Administration, Federal Aviation Administration and U. S. Department of the Navy, have issued their own specifications, but all cite the ASTM specification as a guide.

2.2 Fly Ash Characteristics

2.2.1 Chemical and Physical Properties

Tests indicate that, generally, the strength developed in fly ash-portland cement mortars is related to the carbon content of the fly ash, the fineness of the fly ash measured by the amount passing the #325 sieve, and the water requirement for mortars containing fly ash as compared to similar mortars without fly ash (11). However, the loss on ignition shows no correlation with compressive strength of the mortar (5).

Nevertheless, if fuel oil is burnt concurrently with the coal, small changes in loss on ignition, not directly caused by unburnt coal, may severely retard cement hydration (73).

Differences in SiO_2, Al_2O_3, CaO, MgO, or the sum of SiO_2 and Al_2O_3 contents of fly ash appear to have little significant bearing on the properties of either mortar or concrete (5). However, the SO_3 content of the fly ash appears to have an influence on the early compressive strength; higher SO_3 contents result in higher strengths (5).

2.3 Fly Ash in Portland Cement Concrete

2.3.1 General

Available references relative to the use of fly ash in portland cement concrete are listed in the Reference section of this report. The literature has been reviewed and summarized in logical categories which are then presented in the section entitled Subject Index to References, immediately following the References. In addition, outstanding or particularly relevant comment from the literature has been summarized in this section.

The literature available on the use of fly ash is voluminous. The scope of the presentation here is necessarily limited to highly selective comment on each topic.

2.3.2 Compressive Strength

One-to-one replacement of a portion of the portland cement with fly ash generally results in reduced early strength. However, for a well designed mix, strength beyond 28 days may exceed that of the normal portland cement mix (4, 39). Fly ash must be added in greater quantity than the cement removed to maintain equivalent early age strength (4, 100). In general, curing conditions have the same effect on the compressive strength of fly ash concrete as on normal concrete (9). A definite relationship exists between compressive strength and water requirement for a mortar of fixed consistency (11). The strength of fly ash concrete batched with Type II cement is lower at early age, but higher at late age than similar concrete batched with Type I cement (100).

2.3.3 Flexural Strength (Modulus of Rupture)

High flexural strength in concrete pavement containing fly ash can be obtained with mixes of relatively low cement factor (28). Investigators generally agree that portland pozzolan cement has greater tensile strength than standard portland cement concrete (7).

2.3.4 Workability

Fly ash concrete shows less tendency to separate than concrete not containing fly ash (15, 31), is more plastic, and bleeds less (15). Fly ash in concrete mixes also retards the rate at which the concrete hardens, an advantageous characteristic in hot weather applications where the concrete is exposed to sun and air. However, this retarding effect is not tolerated for cool and cold weather applications and in areas under cover such as basements and floors in homes (87). One study indicates that the addition of finely divided mineral admixtures to concrete without a reduction in cement often entails an increase in the total water content of the concrete and may result in an increase in drying shrinkage and absorptivity as well as a decrease in strength (4). Another study indicates that an 8% sand replacement with fly ash results in a mix of greater workability, even at low slumps (less than 2 inches), for pavements resulting in less shrinkage for a given workability (28, 30). In certain cases, concrete with fly ash has been requested by the concrete finishers who had previously worked with fly ash concrete (30).

2.3.5 Water Reduction

The amount of mixing water required to produce a concrete mix having a given degree of workability is generally less for fly ash mixes than for straight portland cement concrete (8). In one study, mixes with 70 to 188 pounds of fly ash per cubic yard (42 to 112 $\frac{Kg}{m^3}$) required 1 to 2½ gallons less water per cubic yard (0.005 to 0.012 $\frac{m^3}{m^3}$) than comparable non-fly ash mixes of the same consistency (100).

2.3.6 Time of Set

A 25% cement replacement with fly ash can produce concrete that remains workable approximately 2 hours longer at 70°F (21°C) and approximately 4 hours longer when the concrete temperature is 50°F (10°C) (69).

2.3.7 Curing Conditions

Studies indicate that the 28 day strengths of concrete made with or without fly ash respond in the same manner to a given storage condition; moist, dry or cold (10,100). However, fly ash mixes with standard moist curing produce slightly lower strengths prior to 28 days and appreciably higher strengths at lager ages compared to mixes with the same 28 day strength, Type I cement, and no fly ash (10). The fly ash blend also suffers greater strength reductions at the later ages from low temperature curing than the straight Type I cement (10).

2.3.8 Air-Entraining Admixture Demands

Concrete containing fly ash requires larger quantities of air-entraining admixture (AEA) than do concretes not containing fly ash. The increase in AEA with increasing quantities of fly ash varies with quality of fly ash. Both test data and field experience indicate that fly ash concrete requires more AEA than non-fly ash concrete to achieve the same air content (100).

2.3.9 Volume Change

Generally, researchers agree that the use of fly ash in reasonable quantities will not cause excessive drying shrinkage (9, 17, 28). A few studies report drying shrinkage to actually be less for fly ash mixes than for conventional concrete (8, 20, 97). It is also reported that autoclave expansion is considerably lower for fly ash mixes than for straight cement mixes (17).

2.3.10 Creep

A replacement of 15% cement with fly ash (by weight) is found to be the optimum value with respect to creep for the use of fly ash in structural concrete. Creep-time curves for plain and fly ash concretes are similar. Increase in creep with fly ash content is negligible up to 15% replacement, above which creep increases slightly with increasing fly ash content. The probable mechanism of creep is the same for fly ash and normal concrete (44).

2.3.11 Permeability

Concrete is less permeable when a portion of the portland cement is replaced with fly ash (8). Proper use of fly ash as an admixture can reduce permeability from one-sixth to one-seventh that of equivalent concrete containing no fly ash (4).

2.3.12 Freeze-Thaw Durability

The effect of fly ash on the freeze-that durability of concrete is in dispute. Many studies report that fly ash has no effect on the freeze-thaw durability of concrete or that the effect is inconclusive from the tests performed (9, 100). Some reports state that fly ash mixes have freeze-thaw durability characteristics similar to normal concrete mixes if the air contents and compressive strengths are comparable (4, 46). Other reports conclude that fly ash mixes excell over normal mixes in freeze-thaw durability (17, 95). Most studies indicate freeze-that durability to be highly dependent on air content (4, 28, 40, 46, 95, 100).

2.3.13 Sulfate Resistance

All studies reviewed indicated that the resistance of concrete to sulfate attack is improved by the addition of fly ash (4, 8, 17, 20, 28, 39, 73, 100). The effectiveness of fly ash in improving the sulfate resistance of concrete increases as the severity of the exposure to sulfates is increased (4). Special cements for sulfate resistance or for use in marine works may be unnecessary with the correct proportioning of fly ash and portland cement (73).

2.3.14 Surface Scaling

The studies reviewed conflict over the effects of fly ash in concrete on surface scaling. The conclusions range from adverse effect on resistance to surface scaling for all fly ash-portland cement combinations (97) to equal or greater resistance to scaling compared to normal concrete so long as the carbon content of the fly ash remains low (25).

2.3.15 Alkali Reaction

Studies indicate that fly ash is effective in reducing alkali reaction and corresponding mortar expansion (8, 95). Fly ash is more effective in reducing reaction at later ages than at earlier ages (8). However, the use of small amounts of fly ash (less than 10% replacement) along with potentially alkali-reactive combinations may actually increase the rate and severity of alkali-aggregate reaction (65).

2.3.16 Corrosion of Reinforcing Steel

Most sources agree that the addition of fly ash to concrete does not decrease the protection against corrosion of steel reinforcing bars when compared to normal concrete (38, 74, 83, 85). In one study the corrosion potective properties are enhanced by the inclusion of fly ash (39).

2.4 Proportioning Techniques

Several techniques are available for the proportioning of mixes to include fly ash. These techniques utilize a previously tested and proven portland cement concrete mix design by changing the proportions of the different constituents and adding fly ash (46, 53). Strength and workability are held constant between the normal and fly ash mixes (12, 88, 89).

CHAPTER 3. MATERIALS

3.1 General

All materials utilized in the study, excepting the fly ashes, were typical of materials presently used in the manufacture of portland cement concrete in the Phoenix area. Ash from several of the sources had not been used commercially for concrete production in combination with other materials used in the study. In all cases, materials were obtained from normal production runs at commercial production facilities and were not specially produced for use in this study.

Since the study was primarily concerned with variations in concrete characteristics attributable to the use of fly ash as a pozzolanic admixture, it was desired to eliminate, insofar as possible, variations due to constituents other than fly ash. Aggregate, cements and admixtures, therefore, were each obtained from a single source and generally in one purchase lot. All of the materials used (except fly ash) have a history of satisfactory performance in local usage and the general behavior of each of the constituents (except fly ash) has been reasonably well established.

The materials used in the course of the study are described in the following paragraphs. Information on the sources from which materials were obtained is presented in Table 3-1.

3.2 Aggregates

3.2.1 Coarse Aggregate

Coarse aggregate was obtained from alluvial Salt River deposits located in the South Central section of Phoenix, Arizona. The pit-run material in these deposits is typically quite coarse, with an excess

TABLE 3-1. Materials Sources

Material	Source	Remarks
Fly Ash	1. Cholla Power Plant 2. Four Corners Power Plant 3. Navajo Power Plant 4. Mohave Power Plant	Arizona New Mexico Arizona Nevada
Portland Cement	Phoenix Cement Company	Type V* Type II Type IP
Coarse Aggregate	Arizona Sand and Rock (Salt River Source)	ADOT ** Specification 706
Fine Aggregate	Arizona Sand and Rock (Salt River Source)	ADOT Specification 706
Air Entraining Agent	W. R. Grace and Company	Daravair Darex AEA
Water	Phoenix Municipal Water Supply	

* Type II portland cement was used in all fly ash-portland cement concrete mixes. Types IP and V were used for comparative data in selected areas of the study.

** Arizona Department of Transporation

of relatively large rock exceeding 8 inches (20.3 cm.). Crushing is required for balanced production of most aggregate gradations. Some portion of oversize rock is generally wasted in production; nevertheless, aggregate typically contains a large proportion of crushed rock (as compared to screened river run rock). Salt River aggregate is considered, in most respects, one of the better concrete aggregates available in Arizona.

Table 3-2 presents a summary of results derived from tests of the coarse aggregate used in the study. As indicated in Table 3-2, the coarse aggregate was found to be non-reactive when tested in accordance with ASTM C-289 procedures. In the past, Salt River aggregates have occasionally shown a potential for alkali reactivity when tested by this procedure, and reactivity has been experienced in actual use with high alkali cements. This problem has been alleviated with introduction of the production and use of low alkali cement in Arizona, and Salt River aggregate has a long and extensive history of satisfactory performance when used with low alkali cements.

3.2.2 Fine Aggregate

Fine aggregate, obtained from the same source as the coarse aggregate, is predominantly a screened and washed material. Test results of representative samples from the aggregate used in batching the concrete for the study are presented in Table 3-3.

3.3 Portland Cement

The portland cements utilized in the study were produced by Phoenix Cement Company - Division of Amcord, Inc. at a facility located near Clarkdale, Arizona. The cements used

TABLE 3-2. Coarse Aggregate Characteristics

Bulk Specific Gravity (SSD)	Bulk Specific Gravity (OD)	Absorbtion %	Gradation			Dry Rodded Unit Wt. lb./ft^3	Abrasion %	Sodium Sulfate Soundness (Five Cycles) %		Potential Alkali Reactivity
			Sieve Size	% Finer						
AASHO Designation: T84				T27	Spec*	T19	T96	T104	Spec**	ASTM Designation: C289
			1½ in.	100	100					
2.68	2.66	0.75	1 in.	98	95-100					
			3/4 in.	73						
2.68	2.66	0.82	1/2 in.	29	25-60	101.7	13	0.84	12 max.	Aggregate Considered Innocuous
			3/8 in.	14						
2.68	2.66	0.87	1/4 in.	5		101.5				
			#4	1	0-10					
			#8		0-5					

* "Spec" denotes AASHO Designation: M80-70, Size #57, as adopted by ADOT.

** "Spec" denotes AASHO Designation: M80-70.

TABLE 3-3. Fine Aggregate Characteristics

Bulk Specific Gravity (SSD)	Bulk Specific Gravity (OD)	Absorbtion %	Gradation			Sand Equivalent %	Organic Impurities	Fineness Modulus	Sodium Sulfate Soundness (Five Cycles) %	
			Sieve Size	% Finer						
AASHO Designation: T84				T27	Spec*	T176	T21	M6	T104	Spec**
			3/8 in.	100	100					
			1/4 in.	99						
2.65	2.62	0.99	#4	96	95-100	92				
			#8	85						
			#10	81						
2.65	2.62	1.01	#16	70	45-80	91	#1 (clear)	2.76	4.4	10 max.
			#30	45						
			#40	32						
2.65	2.62	0.97	#50	22	10-30	92				
			#100	6	2-10					
			#200	1	0-4					

* "Spec" denotes AASHO Designation: M6-65 as adopted by ADOT.

** "Spec" denotes AASHO Designation: M6-65.

were commercially classified as Types IP, II and V as defined in ASTM Designations: C595 and C150. Type II cement was used in all fly ash concrete batched for the study. Types IP and V were used for comparative purposes in selected portions of the study. Type IP blended cement was used in comparison specimens prepared for compressive strength, flexural strength, sulfate soundness and freeze-thaw testing. Type V sulfate resistant cement was used for comparative specimens in the sulfate soundness test series.

The results of physical and chemical tests performed on samples of cement from the shipments used in the test concrete are presented in Tables 3-4 and 3-5. The cement shipment dated November 14, 1974, was used in the compressive and flexural strength specimens. The later shipment, November 21, 1975, was used for durability and soundness test specimens. The slight difference in cement characteristics, indicated by the data of Tables 3-4 and 3-5, was recognized. Cement from only one shipment was utilized in any given test series. No testing was performed on the Type IP and Type V cements since these cements were not utilized in the batching of fly ash concrete.

3.4 Fly Ash

Fly ash from four sources was utilized in the study. The sources and general locations were:

Four Corners Power Plant	- near Fruitland, New Mexico
Navajo Power Plant	- near Page, Arizona
Mohave Power Plant	- near Laughlin, Nevada
Cholla Power Plant	- near Joseph City, Arizona

Coal used at these plants was obtained from bituminous-to subbituminous sources in Arizona and New Mexico. Information on coal sources and quality is included in Appendix A.

TABLE 3-4. Type II Portland Cement
Physical Test Results

Test Procedure	Shipment Received 11/14/74	Shipment Received 11/21/75	ASTM: C150 Specification
Blaine Fineness, cm^2/gm ASTM: C204	3423	3972	2800 min.
Compressive Strength , psi ASTM: C109 Age 4 days 7 28 60 90	 3110 3230 5200 5930 6420	 - 4140 5380 6380 6960	 2500 min.
Autoclave Expansion, % ASTM: C151	0.04	0.13	0.80 max.
Setting Time, Gillmore ASTM: C266 Initial, Min. Final, Hr.	 310 7.75	 193 5.22	 60 min. 10 max.
Normal Consistency, % ASTM: C187	26.5	25.0	
Specific Gravity ASTM: C188	3.14 3.13	3.12	
Air Content, % ASTM: C185	5.6	6.0 4.9	12 max.

TABLE 3-5. Type II Portland Cement Chemical Test Results

Constituent	Shipment Received 11/14/74 %	Shipment Received 11/21/74 %	ASTM: C150 Specification %
Silicon Dioxide (SiO_2)	21.12	21.14	Min. 21.0
Aluminum Oxide (Al_2O_3)	3.29	3.48	Max. 6.0
Ferric Oxide (Fe_2O_3)	2.38	2.66	Max. 6.0
Calcium Oxide (CaO)	62.13	60.80	–
Magnesium Oxide (MgO)	4.03	4.18	Max. 5.0
Sulfur Trioxide (SO_3)	2.50	2.10	Max. 3.0
Loss on Ignition	1.96	3.66	Max. 3.0
Insoluble Residue	0.79	0.55	Max. 0.75
Tricalcium Aluminate ($3CaO\text{-}Al_2O_3$)	4.69	4.72	Max. 8.0

Test results from samples of the fly ash used in the study specimens are presented in Table 3-6. Periodic sampling and testing of fly ash from each of the sources were performed during the course of the study; however, such sampling and testing were unscheduled and incidental to this study. The data were accumulated for the purpose of providing information on the variation of fly ash properties. Test data relating to the periodic sampling as well as a discussion of the methods of fly ash recovery at each plant are presented in Appendix A.

The data of Table 3-6 apply to samples which represent only the fly ash used in the strength and durability test specimens. Data in Appendix A apply to all samples, and include the results presented in Table 3-6.

The test results indicate that each fly ash failed in some respect to meet the ASTM Designation: C618 for Class F Pozzolan. The failures occurred in the areas of fineness (Blaine surface area and % passing the #325 sieve) and Pozzolanic Activity Index.

3.5 Water and Admixtures

3.5.1 Water Source

The water used in batching concrete test specimens was obtained from the City of Phoenix municipal water supply (laboratory tap water) except where applicable test specifications required distilled water. In general, concrete strength and freeze-thaw specimens were batched with tap water. Sulfate soundness specimens and cement quality specimens were batched with distilled water. No testing was performed on water used in the course of the test program. Table 3-7, however, presents typical data from analyses of the Phoenix water supply.

TABLE 3-6. Fly Ash Used in Strength and Durability Test Specimens

Property *	Cholla	Four Corners	Navajo	Mohave	ASTM: C 618 Class F Specifications
SiO_2 %	58.4	58.4	52.7	52.6	
Al_2O_3 %	31.4	31.4	20.5	16.3	
Fe_2O_3 %	1.3	0.8	4.9	5.5	
Sum of oxides %	91.1	90.6	78.1	74.4	70.0 min.
MgO %			2.0	2.5	-
SO_3 %	0.3	0.3	0.5	1.13	5.0 max.
Moisture %	0.01	0.04	0.02	0.02	3.0 max.
Loss on Ignition %	0.34	0.44	2.77	0.77	12.0 max.
Available Alkalies					
As Na_2O %	0.28	0.52	1.31	1.14	1.5 max.
CaO %	4.5	3.3	8.7	16.4	-
Fineness					
Surface Area cm^2/cm^3	4560	5000	6835	9145	6500 min.
Retained #325 %	36.2	29.8	34.4	36.2	34 max.
Multiple Factor %	12.3	13.1	95.3	27.9	255.0 max.
Pozzolanic Activity Index:					
Cement, % control	60.0	56.0	67.0	84.0	85 min.
Lime, psi	-	-	-	-	800 min.
Water requirement					
% of control	102	98.5	-	-	105 max.
Shrinkage,					
Increase %	0.077	-	-	-	0.03 max.
Soundness,					
Autoclave %	0.048	0.048	0.053	0.13[illegible]	0.5 max.
Expansion - 14 day %	-	-	-	-	0.02 max.
Air-Entraining Admixture ml.	1.68	1.44	-	-	Not applicable
Specific gravity	2.07	1.92	2.12	2.46	Not applicable

*ASTM: C618 Test Series for Class F Pozzolan

3.5.2 Admixtures

No admixtures other than an air entraining agent were used in the concrete. The air entraining admixtures used are described in Table 3-8.

TABLE 3-7. Phoenix Water Supply - Typical Analysis

pH	7.4 - 8.0
Chloride	20 - 465 mgs/1*
Alkalinity, Carbonate	0 - 2 mgs/l
Bicarbonate	110-145 mgs/l
Hardness	120-600 mgs/l
Calcium	22-120 mgs/l
Magnesium	11-67 mgs/l
Total Solids	190-1420 mgs/l
Nitrate	10-180 mgs/l
Fluoride	0.2-1.4 mgs/l
Iron	0-0.1 mgs/l
Sulfate	1-200 mgs/l
Sodium	20-240 mgs/l
Note: The water actually used in the mixes was not tested. This data represents typical values encountered in the City of Phoenix water supply.	

*Milligrams per liter, which is equivalent to parts per million (by weight).

TABLE 3-8. Air Entraining Admixtures

Air Entraining Agent	Manu-factured by	Description	Remarks
Darex AEA	W. R. Grace & Co.	Purified, sulfon-ated hydrocarbon w/cement catalyst	Used in control batches A1, A2, B1, and B2
Daravair	W. R. Grace & Co.	Concentrated aqu-eous solution of completely neutral-ized vinsol resin	Used in all other mixes
Note: Products were not analyzed. Descriptive information was supplied by the manufacturer.			

CHAPTER 4. MIX DESIGNS AND LABORATORY PROCEDURES

4.1 Concrete Mix Designs

4.1.1 General

To meet the objectives of the study, several series of mix designs were developed as a basis for the batching of normal portland cement "control mixes" as well as fly ash concrete mixes. The principal variable in both types of mixes was the volume of cementitious material (portland cement and fly ash). In general the mix designs were developed in accordance with the following considerations:

Coarse aggregate - volume was maintained constant for all mixes, 12.00 $\frac{ft^3}{cy}$ (.0444 $\frac{m^3}{m^3}$).

Fine aggregate - volume was varied from 5.61 to 7.83 $\frac{ft^3}{cy}$ (0.208 to 0.290 $\frac{m^3}{m^3}$) to accommodate changes in cementitious material.

Water - volume was varied from 28.2 to 33.9 $\frac{gal}{cy}$ (0.140 to 0.168 $\frac{m^3}{m^3}$) to maintain workability in the range of 3 $\pm$ 3/4 in. (7.6 $\pm$ 1.9 cm) slump.

Cement and fly ash - total and relative volumes were varied to achieve a suitable range of test data.

Fly ash was the only constituent which varied as to source; four sources were utilized, as described in Chapter 3. Batch weights for all test mixes are included in Appendix B. Mix designs were developed and controlled using absolute volume calculations.

4.1.2 Control Concrete Mixes

Seven control mixes were designed and batched for the study. The first three mix designs (numbers A, B and C) contained 2.90 cubic feet of Type II portland cement per cubic yard (0.107 $\frac{m^3}{m^3}$). This volume, for purposes of relative comparison was designated as 100% cementitious material volume, equivalent to 570 pounds or 6.1 sacks per cubic yard (338 $\frac{kg}{m^3}$). Control mixes 0-0, 0-1, 0-2 and 0-3 were designed with 100%, 90%, 80% and 70% respectively, of the basic control volume of portland cement. This provided a range of control mixes containing from 570 down to 400 pounds or 6.1 to 4.3 sacks of Type II portland cement per cubic yard of concrete (338 to 237 $\frac{kg}{m^3}$).

4.1.3 Fly Ash Concrete Mixes

Several fly ash mixes were studied for each of the four fly ash sources. A coded numbering system was developed to aid in identifying the numerous mix designs. Each mix was identified by a three digit code (such as C-3-2). The first digit identified fly ash source:

C - Cholla
F - Four Corners
M - Mohave
N - Navajo

The second digit identified the volume of cementitious material relative to the base control volume of 2.90 cubic feet per cubic yard (0.082 $\frac{m^3}{m^3}$).

1 - 100%

2 - 110%

3 - 120%

4 - 130%

5 - 140%

The third digit represented the ratios of fly ash and portland cement to the base control volume of cementitious material:

% Control Volume	Third Code Digit	% Fly Ash By Vol.	% Cement By Vol.
100	1	10	90
	2	20	80
	3	30	70
110	1	15	95
	2	25	85
	3	35	75
120	1	25	95
	2	35	85
	3	45	75
140	1	50	90
	2	60	80
	3	70	70

Thus, the mix code C-3-2, for example, would identify the mix as containing Cholla fly ash, 3.48 cubic feet (0.0985 $\frac{m^3}{m^3}$) total cementitious material or 120% of 2.90 cubic feet (0.0821 m^3), 1.02 cubic feet (0.0289 $\frac{m^3}{m^3}$) fly ash or 35% of 2.90 cubic feet (0.0821 $\frac{m^3}{m^3}$), and 2.46 cubic feet (0.0696 $\frac{m^3}{m^3}$) portland cement or 85% of 2.90 cubic feet (0.0821 $\frac{m^3}{m^3}$). Other mixes could be similarly identified, with the exception of those containing

Type IP Cement. The Type IP mixes were identified as follows:

IP-0-0	100% control cementitious material
IP-0-1	90%
IP-0-2	80%
IP-0-3	70%
IP-1-0	110%
IP-2-0	120%
IP-3-0	130%

The proportions of pozzolan to portland cement were not determined for the Type IP, therefore no reference to such proportions is made in this study.

It was generally necessary to mix more than one batch to obtain the concrete necessary for all testing and specimens. A letter (A or B) added as a fourth digit to the mix code identified succeeding batches of the same mix design (i.e., C-3-2A, C-3-2B).

4.2 Concrete Batching and Sampling

4.2.1 Mixing

Concrete for test specimens was batched and mixed in accordance with the Standard Method of Making and Curing Concrete Test Specimens in the Laboratory, AASHO Designation: T126-70 (ASTM Designation: C192-69). Mixing was accomplished in a five cubic foot power-driven revolving drum, tilting mixer. Mortar adhering to the mixer was compensated for by "buttering" the mixer immediately prior to batching. Consistency and air content were determined for each batch. Consistency was determined in accordance with the Standard Method of Test for Slump of Portland Cement Concrete, AASHO Designation: T119-70 (ASTM Designation: C143-69). Air content was determined in accordance with the Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method, AASHO Designation: T152-70 (ASTM Designation: C231-68). Batches not meeting the requirements for air content or consistency were rejected with the exception that water was occasionally added to low-slump batches and mix proportions were recalculated accordingly.

4.2.2 Compressive Strength Test Specimens

Compressive strength test specimens were cast in 6 in. (15.2 cm) diameter by 12 in. (30.5 cm) high cylindrical metal molds. Sampling and casting of specimens were accomplished in accordance with the procedures of AASHO Designation: T126-70. Consolidation was accomplished by rodding. Cylinders were stored in the moist room prior to stripping and moist curing. After stripping, cylinders were stored in a moist room in accordance with the recommendations for Moist Cabinets and Rooms Used in the Testing of Hydraulic Cements and Concrete, AASHO Designation: M201-70 (ASTM Designation: C511-68). Three test cylinders were cast for each planned test age.

4.2.3 Flexural Strength Test Specimens

Specimens for determination of flexural strength were cast in 6 x 6 x 20½ in. (15.2 x 15.2 x 52.1 cm) metal molds in accordance with the requirements of AASHO Designation: T126-70. Consolidation was accomplished by rodding. Three beams were cast for each test age. Prior to stripping, beams were stored in the moist room. Curing was accomplished in a moist room in accordance with the provisions of AASHO Designation: M201-70 (ASTM Designation: C511-68).

4.2.4 Freeze-Thaw Specimens

Specimens for durability tests in the freeze-thaw apparatus were cast in 3 x 3 x 15 in. (7.6 x 7.6 x 38.1 cm) metal molds. Specimens were cast in companion groups of three and cured in accordance with the provisions of ASTM Designation: C666-73, Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing. Concrete was batched separately from that used for strength determination specimens.

4.2.5 Sulfate Soundness Test Specimens

The specimens for determination of resistance to sulfate attack were cast in metal 1 in. (2.54 cm) cube and 1 x 1 x 11 in. (2.54 x 2.54 x 27.9 cm) bar molds. The batching, specimen molding and curing were in accordance with a non-standardized procedure which is outlined in detail in the section on durability testing (Chapter 6).

4.3 Curing and Testing

4.3.1 Curing

Cylinders and beams for compressive and flexural strength testing were cured until test age in a standard moist room as mentioned previously. Temperature and humidity in the moist room were automatically controlled and recorded.

4.3.2 Strength Testing

Compressive strength testing was performed in accordance with the requirements of AASHO Designation: T22-66 (ASTM Designation: C39-66). Third point loading was used for the determination of flexural strengths, in accordance with AASHO Designation: T97-64 (ASTM Designation: C78-64).

CHAPTER 5. COMPRESSIVE AND FLEXURAL STRENGTH

5.1 Compressive Strength

5.1.1 Test Results

Compressive strength test data are tabulated in Appendix B. Each reported value represents an average of three test results. Batch weight, air content, slump, unit weight and temperature are included with the strength data for convenience of reference.

Figures 5-1a, b and c present age-strength curves representing all compressive strength data tabulated in Appendix B. The curves are organized in accordance with test series designations. Detailed batch information on each series is presented in Appendix B and an explanation of the series designation meanings in Chapter 4. It should be noted here that many factors which are constant in the mix designs of this study, are variables in the general case. Such factors include consistency, air content, coarse aggregate content, aggregate quality, portland cement quality and conditions of curing.

Each set of curves in Figures 5-1a, b and c represents concrete mixes with the same proportions of portland cement and fly ash. The mix designs produced a general range of 28 day compressive strengths varying from 2200 to 4720 psi (155 to 332 Kg/cm^2).
The primary differences in the curves reflect strength variations caused by differences in fly ash characteristics from the various sources. Some trends are apparent. The Navajo fly ash concretes consistently exhibit the highest strengths, and Cholla the lowest, at early ages (up to 28 days). At later ages (60 and 90 days) this trend is not

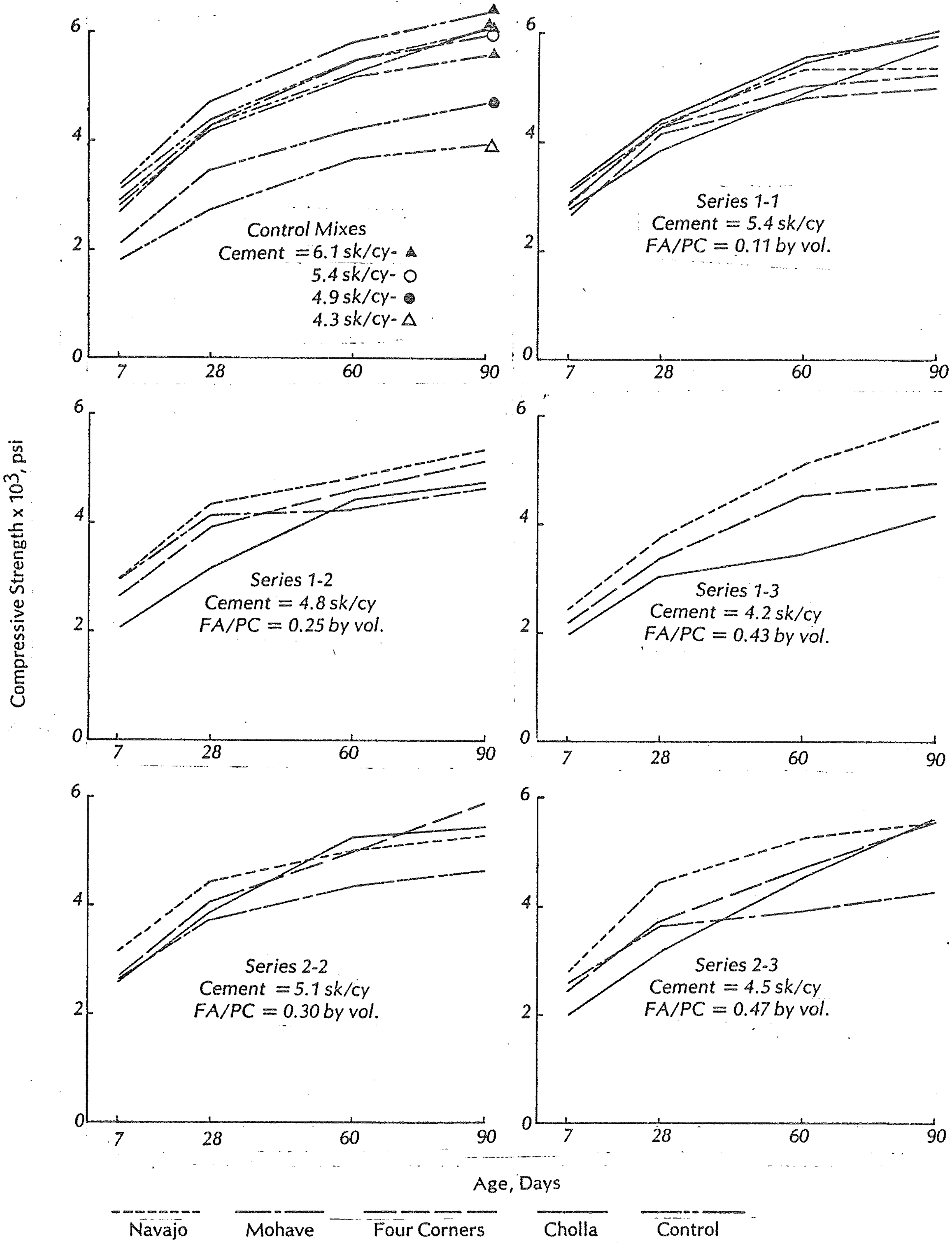

FIGURE 5-1A. COMPRESSIVE STRENGTH VS. AGE

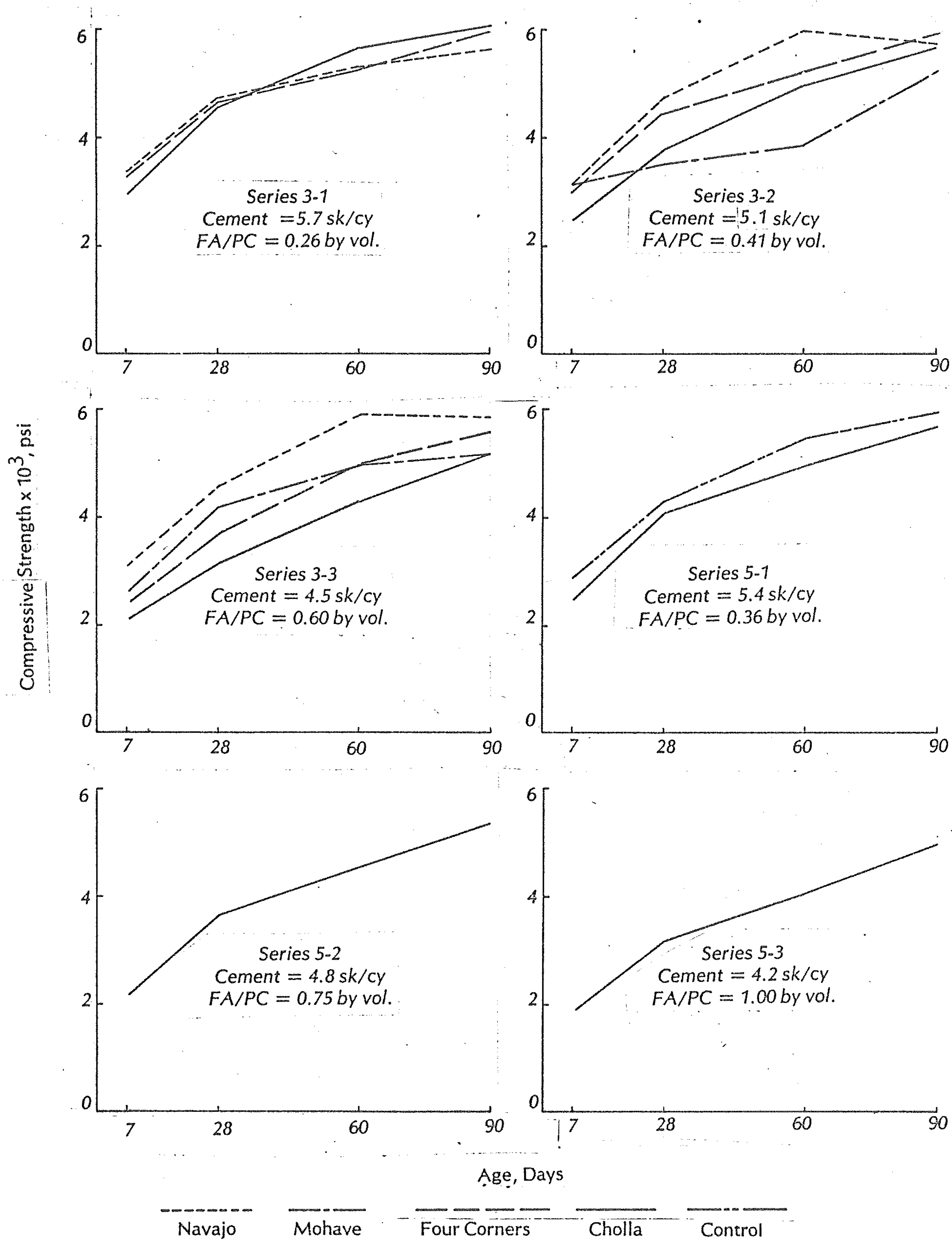

FIGURE 5-1B. COMPRESSIVE STRENGTH VS. AGE

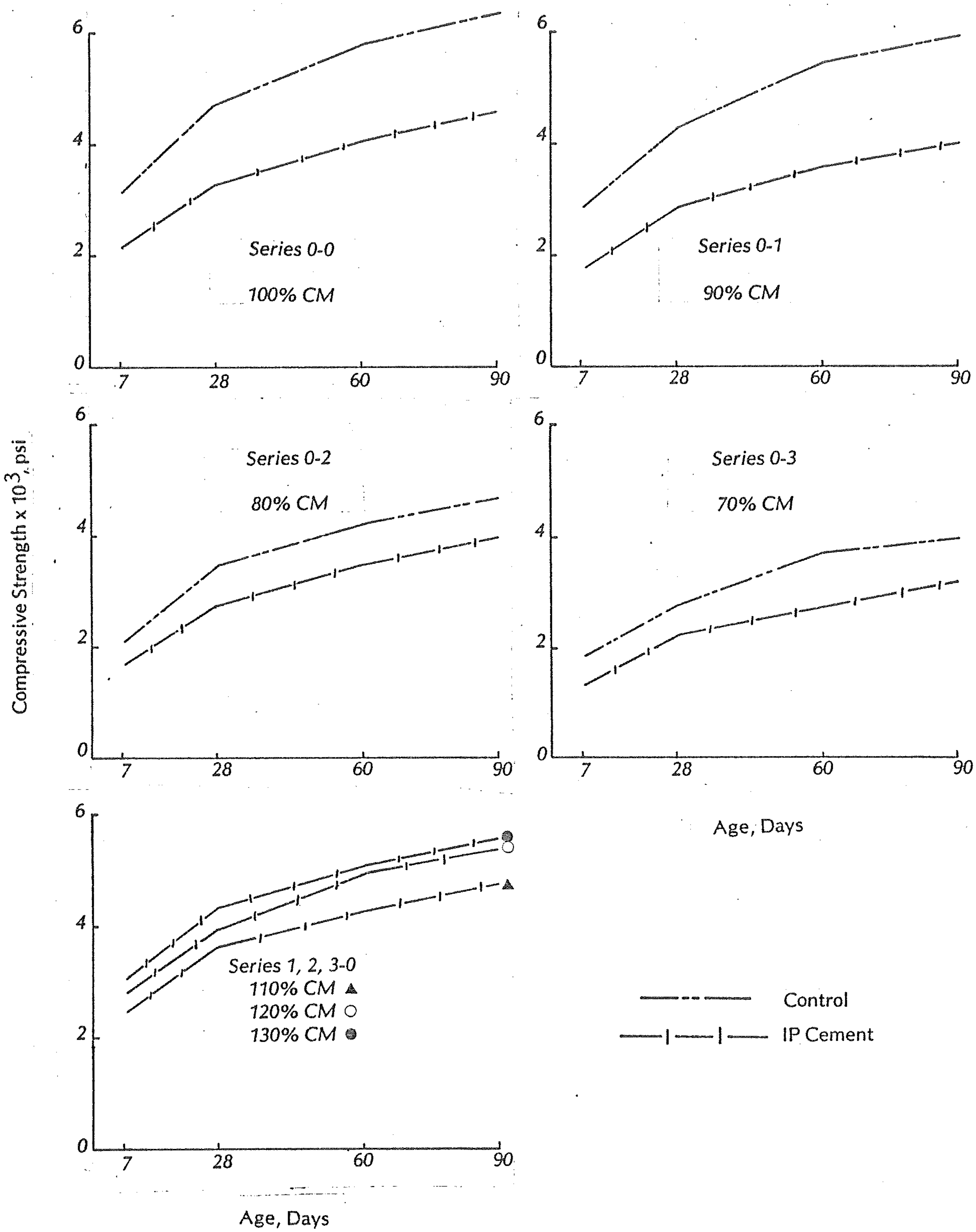

FIGURE 5-1C. COMPRESSIVE STRENGTH VS. AGE dominant. The Cholla fly ash concrete generally shows a strong late-age gain relative to the three other sources.

Strength gain with time is discussed further in the following paragraphs. The statistically derived comparisons and evaluations are essentially correlations and are not necessarily intended to represent cause-effect relationships. This fact should not handicap the usefulness of the analysis.

5.1.2 General Age-Strength Relationship

The projection of early age compressive strengths to later age predictions is a continuing problem in concrete quality control. The pace of construction is frequently such that 28 day, or later, compressive strength test results are often of little practical value for quality control during construction, or even for the development of mix designs. Specifications, nevertheless, are generally developed around 28 day compressive strengths, and acceptance based on these relatively late age test results. To avoid serious problems with regard to acceptance of in-place non-specification concrete, as well as potential safety hazards posed by low strength concrete supporting subsequent superstructure, strength projections must be based on early age test results, general knowledge of the uniformity of the concrete batching and handling procedures, and intuition. The problem is well known, widely recognized and has been discussed thoroughly in many volumes of published literature.

The compressive strength data developed during the course of this study were analyzed to determine if the strength gain with age of fly ash concretes could be reliably predicted. Data available included 7, 28, 60 and 90 day compressive strengths for all mix designs studied. Three expressions for the prediction of compressive strength were examined. The consideration of these mathematical models is, in itself, an exercise which gives considerable insight into strength gain.

The first expression was of the general form

$Y = AX^B$, in which:

- Y = Compressive strength at desired age, psi
- X = Age at which compressive strength is desired, days
- A = Constant coefficient
- B = Constant exponent

This expression was examined since concrete strength gain with time appears generally to develop in accordance with a relationship of this type.

The second expression analyzed was of the general form

$Y = X + AX^B$, in which:

- Y = Compressive strength at age 28 days, psi
- A = Constant coefficient applicable to 28 day prediction only
- X = 7 day compressive strength, psi
- B = Constant exponent applicable only to 28 day prediction

This expression differs from the first in that the independent variable is a strength value rather than an age; further the dependent variable is not an explicit function of time.

The third expression studied was of the general form

$Y = A + BX_1 + CX_2$, in which:

Y = Compressive strength, psi
A, B, C = Constants
X_1 = Portland cement content, lb./cy
X_2 = Age, days

The last expression has been included here since it has been noted in the reference literature.

There are numerous relationships which can be examined in any attempt to develop a mathematical model to explain concrete strength gain. Various logical transformations of the selected independent variables add further to the variety of possibilities. The development of the "best" such model was not a purpose of this study. The models included in this study were selected on the basis of common usage or presentation in the existing literature. The purpose herein is to provide a basis of judgment for the predictability of fly ash concrete compressive strength.

5.1.2.1 Age Regression Model

The expression $Y + AX^B$ was analyzed by fitting all test data (7, 28, 60 and 90 day compressive strengths) utilizing a least squares analysis to obtain "best fit". The constants "A" and "B" were determined for each test series as were the coefficients of determination for the data-fit. The coefficients of determination were found to be above 0.950 for about 92% of the 48 test series data points and above 0.980 for about 77% of the data points. The relatively high values of the coefficients of determination indicated that the strength gain with age could be well represented by a general geometric regression. Most of the data which exhibited lower correlation occurred in the Mohave fly ash mix design series. The general shapes of age-strength curves for the Mohave series (Figures 5-1a, b and c) illustrate the slightly erratic results.

The constants "A" and "B" in the general regression equation naturally varied widely for the different mix design series. To determine whether or not a reliable strength prediction could be developed, further regression analyses on the constants "A" and "B" were performed, utilizing geometric, linear and exponential regression functions. The 7 day compressive strengths were used as the bases for these analyses. In the case of each regression, three relationships were examined; 7 day compressive strength vs "A"; 7 day compressive strength vs "B"; and "A" vs "B". A minimum of 90% of the variation in "A" was found to be explainable by either of the three regressions. The geometric function yielded the best correlation for "A". The best predictions of "B" were developed from the linear regression expression, utilizing "A" as the dependent variable, rather than 7 day strength. Results indicated that 74% to 96% of the variation in "B" could be explained by the model; correlation was slightly less positive than for the constant "A".

The expression for the prediction of later age compressive strengths based on 7 day test results would be:

$$\sigma_X = AX^B$$

in which

σ_X = Compressive strength at desired age, psi

X = Age at which compressive strength prediction is desired, days

and the "best fit" values of "A" and "B" were found to be:

Fly ash mixes $A = 5.471 \times 10^{-3}\ \sigma_7^{\ 1.595}$

$B = 4.875 \times 10^{-1} - 1.313 \times 10^{-4} A$

Control mixes $A = 1.651 \times 10^{-1}\ \sigma_7^{1.157}$

$B = 3.889 \times 10^{-1} - 6.180 \times 10^{-5} A$

Type IP mixes $A = 8.510 \times 10^{-2}\ \sigma_7^{1.248}$

$B = 4.096 \times 10^{-1} - 9.056 \times 10^{-5} A$

where σ_7 = compressive strength at age seven days, psi.

Compressive strengths were predicted for 28, 60 and 90 day ages using the power curve and constants derived above. Actual vs predicted values of 28 day compressive strength are presented in the scatter diagram Figure 5-2. The data indicate reasonably good correlation, with nearly all data falling within the $\pm$ 10% range. The points falling marginally within the $\pm$ 10% range are predominantly from the Mohave fly ash series.

It should be noted here that the resultant relationships are not presented as the best possible representation of the strength-time relationship nor are the relationships necessarily universal. The purpose here is to present a reasonably reliable model for compressive strength prediction which can be used to evaluate two questions:

1) Is the compressive strength of fly ash concrete predictable?

and 2) How do the strength-time characteristics of fly ash and normal concretes compare?

The data indicate the answer to the first question appears to be in the affirmative. The fly ash test mix designs appear to be predictable within the range of accuracy expected of normal portland cement concrete. Examining Figure 5-2 it appears that the Control and Type IP mixes fit more closely to the 45° "perfect prediction" line than

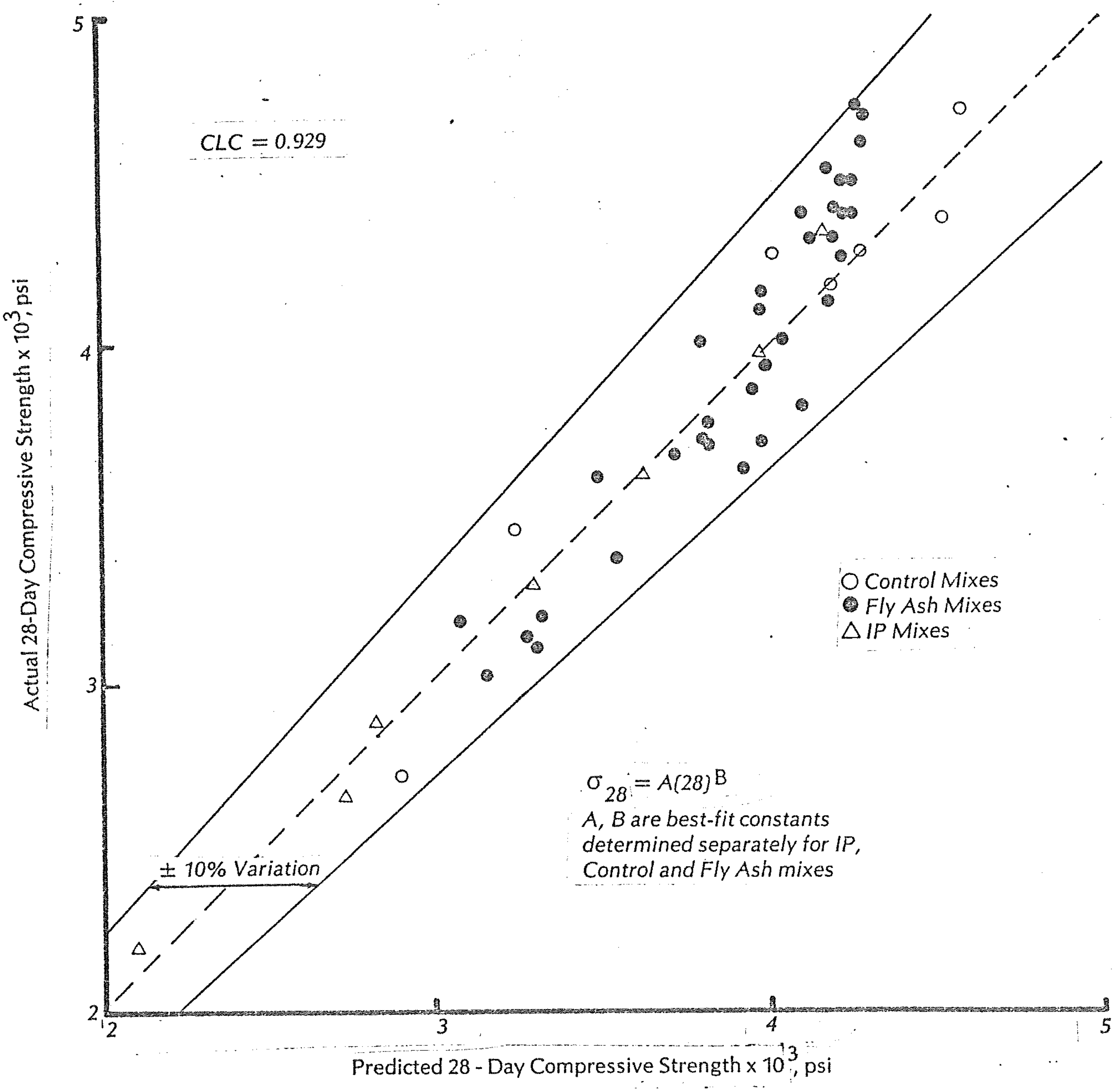

FIGURE 5-2. ACTUAL VS. PREDICTED 28-DAY COMPRESSIVE STRENGTHS

do the fly ash mixes. It should be remembered, however, that the constants in the regression equation were developed separately for Control, Type IP and Fly Ash mixes. Separate determination of constants for each fly ash source would probably improve correlation for the fly ash mixes. However, the data as presented serve to demonstrate the general answer to the questions of compressive strength predictability.

The resultant relationships, presented in Figure 5-3, illustrate the apparent general strength gain behavior exhibited by the test mixes, and analysis thereof can provide insight regarding the second question. The data developed indicate that at relatively low compressive strengths the fly ash concretes realize a greater strength gain than do normal concretes when compared with equal 7 day strengths. Conversely, the data indicate that for a given late-age strength (28 to 90 days) the normal concrete must have a higher seven day strength. This is consistent with much of the current general knowledge available regarding fly ash concrete strength gain. Higher strength mix designs lead to a reversal in this trend as indicated by the set of curves originating at a seven day strength of 3000 psi (211 Kg/cm^2).
Again, general experience in the field of fly ash mix designs seems to indicate the fly ash concretes are less efficient in the higher strength ranges. It should not be implied that the strength gain beyond 90

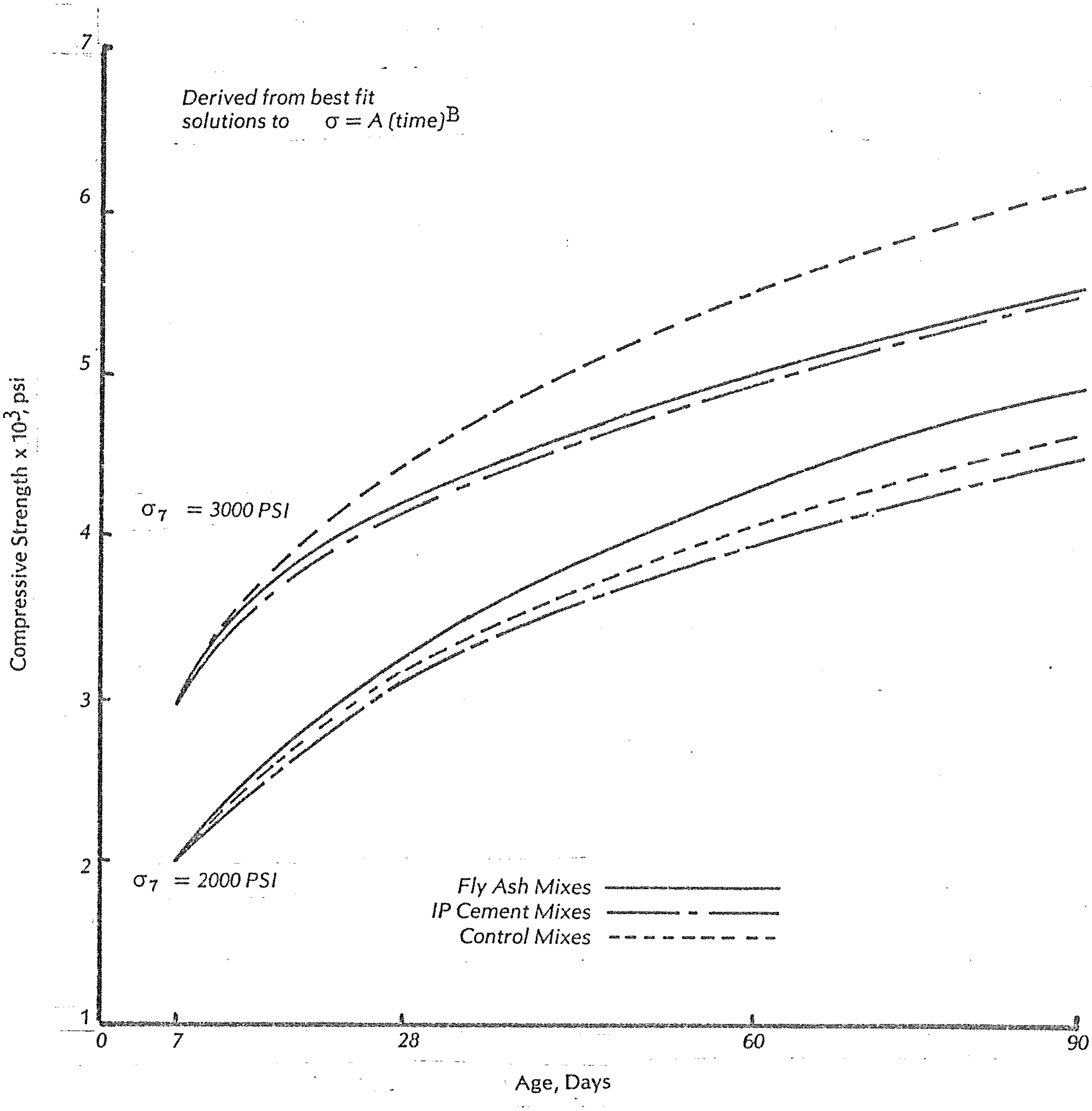

FIGURE 5-3. RELATIVE STRENGTH GAIN

days would continue at the rates indicated by the curves. The curves represent only the best fit to the available data from 7 to 90 days and may not be extended without new evaluations of the curve constants utilizing data points in the later (beyond 90 days) ages.

The curves of Figure 5-3 represent the best fit of the data developed from the tested mix designs; conclusions based on the curves should be developed only with full knowledge of the particular mix designs included in the study.

5.1.2.2 7 Day vs 28 Day Compressive Strength Model

The relationship:

$$\sigma_{28} = \sigma_7 + 30\sqrt{\sigma_7}\ , \text{ in which } \sigma_7 \text{ and } \sigma_{28}$$

are 7 and 28 day compressive strengths, is frequently employed (at least in the geographic area common to this study) as a means of estimating 28 day compressive strength from the 7 day test result. This appears to have been derived from a transformed polynomial regression using 7 day strength as the independent variable. The expression was evaluated in its usual form; the results of the evaluation can best be summarized by reference to the upper scatter diagram of Figure 5-4. The control (normal concrete), IP cement and fly ash mixes are presented identifiably for comparison. The relative linearity of the predicted vs actual compressive strengths is indicated by the

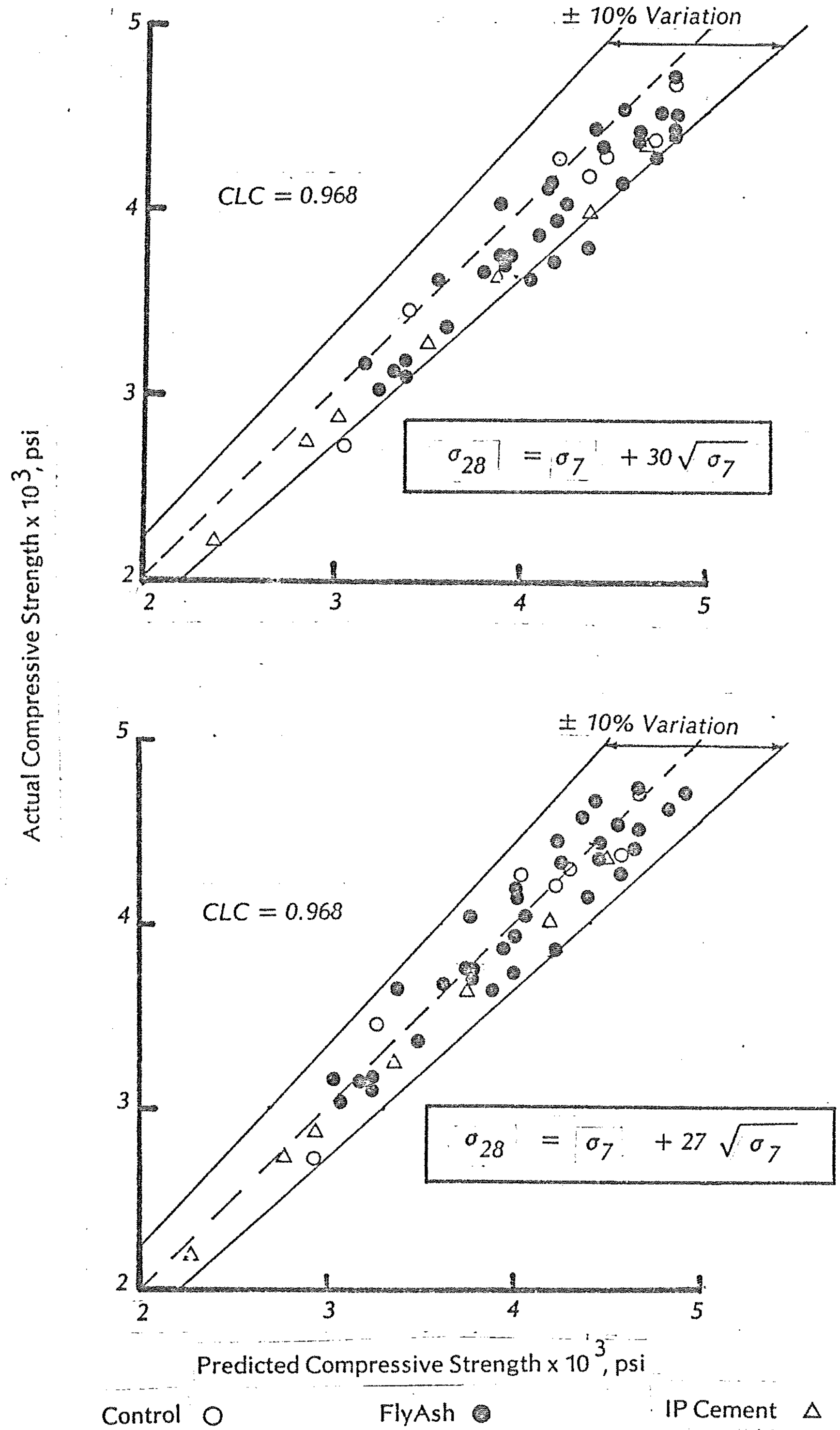

FIGURE 5-4. ACTUAL VS. PREDICTED COMPRESSIVE STRENGTH

coefficient of linear correlation given on the figure. The coefficient of linear correlation for the scatter diagram can in this case be interpreted as the coefficient of correlation for the original data points to the model equation. The coefficient of determination therefore, indicating the percentage of variation accounted for by the model equation, can be taken, for practical purposes, as the square of the coefficient of linear correlation. Thus the model equation appears to account for about 94% of the variation in 28 day compressive strength.

The upper portion of Figure 5-4 includes all data developed in the course of this study; and the coefficient of linear correlation (CLC) includes all data with no distinction for mix type. Actual strength appears to consistently fall short of the predicted value; therefore, a logically indicated but arbitrary change of constant from 30 to 27 was similarly evaluated with better results. The lower scatter diagram of Figure 5-4 illustrates the latter evaluation. The relationship appears to be reasonably valid for projection of 28 day compressive strengths within a range of error of $\pm$ 10%.

The likely rationale behind the development of the equation can readily be seen by reference to Figure 5-5. The corresponding 7 and 28 day compressive strengths are plotted on the scatter disgram for all mix designs studied. The distribution of data points

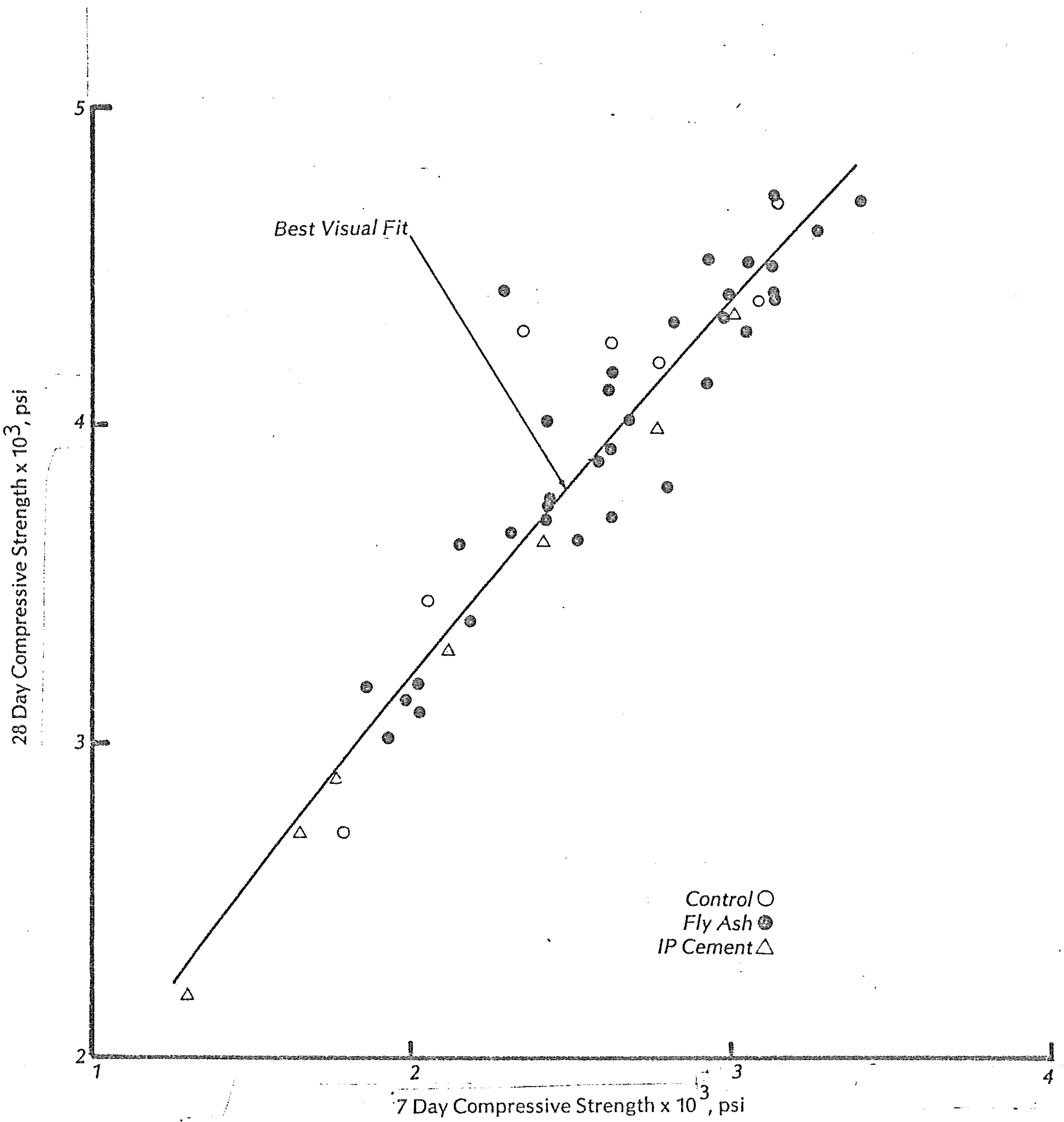

FIGURE 5-5. 7 DAY VS. 28 DAY COMPRESSIVE STRENGTH

suggests that the relationship might be approximated by a best fit polynomial. The least squares best fit solution to the general polynomial equation ($Y = A + BX + CX^2$, transformed by $X_1 = X^2$) yielded the solution:

$$\sigma_{28} = -16{,}670 - 5.9\ \sigma_7 + 711\sqrt{\sigma_7}$$

based on control mix data only. Small changes in data distribution result in large changes in individual coefficients. This best fit solution increased the reliability of prediction to a slight degree. The best fit solution to the general polynomial appeared to account for about 97% of the variation in 28 day compressive strength. The slight increase in reliability gained by this refinement is not of practical value considering the increased complexity of the expression.

Solutions could be examined for the polynomial relationship in various degrees, and with various logical transformations of the independent variable, to find the best representation of the data. Comparisons between fly ash and normal concrete behavior could also be developed at all ages. This approach would be one of the nearly limitless avenues of investigation, mentioned earlier, that could result from the data developed in this report. The purpose of this brief section, however, was merely to examine the 7 to 28 day strength gain of fly ash concrete rela-